Astrophysics at n_TOF Facility at CERN

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Abstract. The neutron time of flight (n_TOF) facility at CERN is a spallation neutron source with white neutron energy spectrum (from thermal to several GeV), covering the full energy range of interest for nuclear astrophysics, in particular for measurements of the neutron capture cross section required in s-process nucleosynthesis. This contribution presents an overview on the astrophysical program carried on at the n_TOF facility, the main results and their implications.

1. The n_TOF facility at CERN

Based on an idea by Rubbia et al. [1], the n_TOF facility at CERN, Geneva, Switzerland, became fully operational in May 2002. After commissioning of the neutron beam, an intense scientific program started, relevance for Nuclear Astrophysics and energy applications. At n_TOF, neutrons are produced via spallation reactions induced by a pulsed proton beam on a massive lead target of 80 x 80 x 60 cm^3. The high proton momentum of 20 GeV/c, the short pulse width of 6 ns, and an intensity of $7 \cdot 10^{12}$ protons per pulse make n_TOF one of the most luminous neutron source world wide. A 5 cm water slab surrounds the lead target acting as a coolant and as moderator of the initial fast neutron spectrum. As a result, a white neutron spectrum ranging form thermal up to a few GeV is produced [2].

Neutrons emerging from the target propagate in the vacuum pipe inside a time-of-flight tunnel 200 m long. Two collimators are present along the flight path, one of the diameter of 13,5 cm placed at 135 m from the lead target and one at 180 m with a diameter of 2 cm for the capture measurements. This collimation results in a Gaussian-shaped beam profile [3]. A 1.5 T sweeping magnet placed at 40 m upstream of the experimental area is used to deflect outside the beam charged particles travelling along the vacuum pipe. For an efficient background suppression, several concrete and iron walls are placed along the time-of-flight tunnel.

The measuring station is located inside the tunnel, centered at 187.5 m from the spallation target.

Two complementary setups for neutron capture measurement are used at n_TOF: a pair of specifically designed C_6D_6 [4], and a 4π BaF_2 array [5] acting as a total absorption calorimeter (TAC).

Due to the low cross-section of most the samples of Astrophysics interest measured at n_TOF, the C_6D_6 were preferred for these measurements, since these detectors have the advantage of presenting an extremely low sensitivity to scattered neutron.

The data acquisition system is based on flash ADCs with sampling rate up to 1 GHz. The consequent very high data rate ensures an almost zero dead-time [6].

2. Experimental campaign

The experimental campaign devoted to Nuclear Astrophysics is focused mostly on neutron magic nuclei, which act as bottle neck for the flow of s-process. Branching points isotopes and isotopes of special interest, such as the osmium involved in the so-called cosmic clock have also been investigated. Many new relevant results have been achieved, see [7,8,9,10,11,12]. In the following, the most recent result and their astrophysica implications are described.

2.1. $^{90,91,92,93,94,96}Zr$ (n, γ) cross section measurements

Zr is a typical s-process element belonging to the first s-process peak of solar abundance distribution. Predictions of the production of the various Zr isotopes are critical for s-process modelling. Several of them are close to the magic number of neutron N =50, with ^{90}Zr having exactly N=50. Hence, production of $^{90,91,92,94}Zr$ is sensitive to the overall neutron flux, which is mostly defined by the ^{13}C neutron source. The abundance of the remaining stable isotope, ^{96}Zr, is determined by the activation of the branching point at the unstable ^{95}Zr. Hence, its production is sensitive to the neutron density, which is mostly defined by the ^{22}Ne neutron source. Furthermore, most of the abundance of the element Nb is due to the radiogenic decay of the long living ^{93}Zr.

The capture cross sections of the ^{91,92,93,94,96}Zr in term of resonance parameter were measured in a wide neutron energy range. The results [13,14,15,16] show sizeable differences with respect to previous experimental data and allow extracting the related nuclear quantities with improved accuracy.

2.2. ^{186,187,188}Os(n, γ) measurements

The time duration of the nucleosynthesis of the heavy elements produced by neutron capture processes can be used to set limits on the age of the universe [14]. Among several cosmic clock based on the abundances of long-lived radioactive isotopes, the ^{187}Os/^{187}Re is one of the most interesting.

The clock is based on the extremely long half-life of ^{187}Re($\tau_{1/2}$ = 43.3Gyr), decaying to ^{187}Os, and on the fact that ^{186}Os and ^{187}Os are shielded against direct r-process production. Thanks to the well established s-process abundances of the ^{186}Os and ^{187}Os, the age of the Universe can be inferred, in the the Re/Os clock, by the enhancement in the abundance of ^{187}Os due to ^{187}Re $\rightarrow ^{187}$Os decay.

The neutron capture cross sections of ^{186,187,188}Os have been measured at the CERN n_TOF facility with improved accuracy and over a wide energy range of neutron energies from 1 eV to 1 MeV. In Fig. 1 a comparison between the n_TOF result and the previous data is shown. Based on the n_TOF data,Maxwellian averaged cross sections have been obtained with uncertainties between 3 and 4%. These results have been complemented by a detailed resonance analysis.Average level spacing, radiative widths, and neutron strength functions have been deduced by statistical analysis to establish a consistent set of input data for detailed cross section calculations with the Hauser-Feshbach statistical model. Based on these calculations stellar enhancement factors were obtained to correct the Maxwellian averaged cross sections determined from experimental (n,γ) data for the effect of thermally excited states in the hot, dense photon bath at the *s*-process site. The corresponding stellar (n,γ) cross sections have been used to separate the radiogenic part of the ^{187}Os abundance from its *s*-process component and to define the mother/daughter ratio ^{187}Re/^{187}Os. With a schematic model that assumes an exponentially decreasing production rate for ^{187}Re, an age of the Universe of 14.94 Gyr was obtained from the Re/Os cosmo-cronometer, with an accuracy, mostly related to the remaining nuclear physics uncertainties, of less than 1 Gyr. More details can be found in [17,18,19,20]

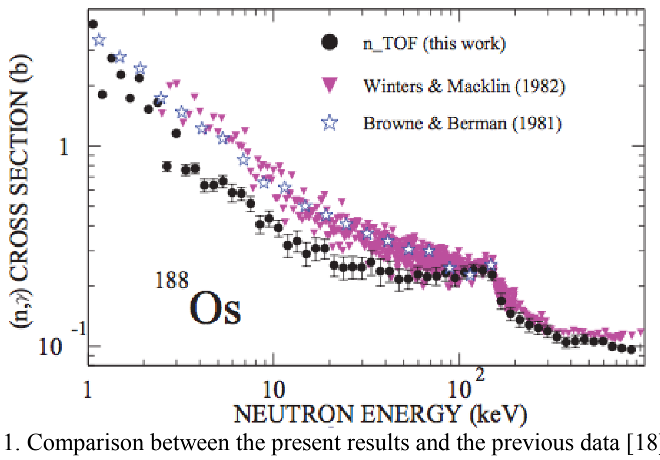

FIG. 1. Comparison between the present results and the previous data [18]

Conclusion

Neutron capture cross sections of astrophysical interest have been measured at the CERN n_TOF facility. The major motivation of these measurements was to reduce the uncertainties on nuclear data to a few percent, as required to improve the stellar s-process model. Improvements in the n_TOF apparatus, compared to previous experiments, resulted in significantly reduced uncertainty in the measured cross-sections, with a valuable impact on studies of s-process nucleosynthesis. New measurements on neutron-magic nuclei and, especially, on branching-point radioactive isotopes, are foreseen at n_TOF for the near future, while a much higher neutron flux in a second experimental area at 20 m from the spallation target, now in the proposal phase, would open the way to measurements of relatively short-lived isotopes, produced at ISOLDE, involved in r-process nucleosynthesis.

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